CynerG: Integrating Computational Visualization with Exploration of Geohazards

Importance

The recent images of lava flowing out of Kilauea are nothing short of remarkable. Watching the videos—as lava cuts across roads and trees go up in flames—is both terrifying and compelling. As of this writing, lava from the Hawaiian volcano has destroyed hundreds of structures and displaced thousands of residents from their homes. Although geoscientists cannot predict the future exactly, they are continuously engaged in analyzing Earth's clues to make forecasts and perhaps save human lives as a result while understanding more and more about geohazards. To improve volcanism forecasts, scientists rely on scientific instruments that collect information about deformation, seismic signals, and more.

Data are critical for exploring these real-world geohazards. With the advancement in remote sensing technologies embedded in satellites and large networked science observatories, high-quality data are being continuously collected in large quantities around the globe [1] and are available to scientists who study geohazards, such as earthquakes, volcanoes, and tsunamis. Geohazards, the geological processes that may lead to risks and damages to human and natural resources, can be small with an impact only on a relatively minor local area such as a landslide or they can affect entire cities such as earthquakes. While geologists cannot prevent the Earth from causing hazards, their goal is to better understand the mechanisms and impacts associated with those hazards and improve their ability to assess risks. This in turn can help citizens make informed decisions and take appropriate actions by considering their local community's vulnerability and exposure to the impending risk [2], [3].

Much of geohazard research involves computational analyses and visualizations of large data sets [4]. However, large data sets from sensing technologies can neither be simply manipulated nor be manually analyzed without some level of automation. As such, geohazard scientists create and interpret computationally processed visualizations as a way to discover both spatial patterns across areas as well as temporal trends, so that the location and the impact of hazards can be more precisely predicted. Some tasks involved in monitoring and tracking are routine and repetitive. These tasks include writing and running algorithms to manipulate data sets (e.g., standardizing, reformatting, or filtering), analyzing data through statistical analysis, plotting many different data inputs, and collating the results for analysis [5]. In geohazard research, enhanced computing power enables big data conversion, simulation, and visualization to play a greater role in discovery and prediction, which are critical when considering risk analysis. Arguably the field of geohazard science is rapidly changing to a point where discoveries and innovations are coming predominantly from those who can translate a scientific idea into an algorithm, and then into a series of codes expressed in a computational language.

Geohazards, therefore, offer an ideal curricular context for students to experience integrated practices between science and computational thinking. Geohazards are not only scientifically important, they are also captivating to students. Geohazard scientists often rely on computationally generated visualizations of data as a way to explore Earth systems, so it is a natural place to embed computational thinking in classrooms. The Next Generation Science Standards (NGSS) [6] advocates for the inclusion of natural hazards content in Earth science classes in both middle and high school. Specifically, the NGSS suggests that students should analyze and interpret data on natural hazards in order to consider their potential impact, mitigate their effects, and use scientific evidence to build student understanding.

Goals and Objectives

The primary goal of CynerG is to develop a pedagogical model for integrating science practices with computational thinking practices germane to geoscientists' inquiry into geohazards. In this project, core computational practices will occur in the construction, interpretation, and revision of computational visualizations to explain scientific phenomena [7], [8], make predictions, and assess impacts. Students

will engage in the practice of scientific argumentation in order to "formulate and answer questions using data as part of evidence-based thinking" [9, p. 1]. Our approach will leverage access to vast amounts of data to fundamentally improve teaching and learning of Earth science by integrating key science concepts with the development of code for representing data in accessible visualizations. Through this work we aim to empower secondary students' scientific problem-solving through the deliberate synergistic interweaving of both disciplines by exploring case studies of real-world volcanic and seismic geohazards. The Concord Consortium (CC), in partnership with experts in understanding hazards using geodesy at UNAVCO, and geologists from the University of South Florida (USF), proposes *CynerG*: *Integrating Computational Visualization with Exploration of Geohazards* to design and develop curriculum resources for middle and high school Earth science students. The objectives of this project are:

- Objective 1. Develop A Scaffolded Visualization Programming (SVP) tool and NGSS-aligned science curriculum materials. The CynerG project will create an open-source online SVP tool to enable students to create visualizations. The SVP tool will leverage a block programming paradigm, but will gradually require the learner to code text-based programming in JavaScript. The project will also develop two online inquiry-based, geohazard curriculum modules addressing earthquake and volcano geohazards. The SVP tool will be embedded in these modules.
- **Objective 2: Conduct targeted research on student learning.** Research will occur in two phases. The first phase will iteratively refine the SVP tool, curriculum modules, and assessments. The project will also investigate the supports necessary to fully engage teachers and students in successfully implementing the curriculum modules. The second phase will investigate the added benefits of integration of the computational practice of developing geoscience visualizations on science learning using a delayed cohort design.
- **Objective 3: Disseminate project products and research findings.** We will distribute curriculum and assessment materials along with the SVP tool for free on the CC and UNAVCO websites. We will promote the materials and the research findings at major conferences and in peer-reviewed journals targeted for geoscientists, educational researchers, and teacher practitioners.

Results from Prior NSF Support

The High-Adventure Science (HAS) and High-Adventure Science: Earth's Systems and Sustainability (HAS: ESS) projects (PI: Pallant; Co-PIs: Lee and Larson; DRL-0929774; \$695,075; 9/15/09 – 8/31/12; DRL-1220756; \$2,328,593; 10/1/12 – 12/31/16). *Summary of project results:* This pair of HAS projects developed six modules to test the hypothesis that students who use computational models of complex Earth systems, analyze real-world data, and engage in scientific argumentation practices will be better able to understand core ideas about Earth systems science and the impact humans can have on these systems. Analysis of pre- and post-tests showed significant improvement in student argumentation and systems dynamics thinking across diverse school settings-student argumentation improved by effect sizes (Cohen's d) ranging from 0.35 to 0.54. Intellectual merit: These projects have manifested four design principles to address how to incorporate scientists' current empirical research and modeling practices into short duration, inquiry-based curriculum modules. These projects have created and validated two separate assessment frameworks: uncertainty-infused scientific argumentation and system dynamics thinking related to Earth systems. Broader impacts: The HAS modules have been distributed widely for free through the National Geographic Society and CC websites. As of today, 132 teachers and approximately 6,300 students have participated in field-testing. In addition, Google Analytics shows 210,000 visitors to the HAS website in 2017, producing a large and growing independent community of registered users (67,000 registered users) across all 50 states. Publications: This work has been extensively documented in six peer-reviewed research publications for assessing students' uncertainty-infused scientific arguments [10], analyzing student articulation of uncertainty in argumentation [11], specifying a methodology for promoting scientific argumentation using computational models [12], a method for

using stocks and flows as a framework to structure students' exploration of models and thinking about sustainability [13], and instructional dilemmas and opportunities provided by the use of digital curricula [14]. In addition, five peer-reviewed papers were published in teacher journals [15]–[20]; and five newsletter articles were published [21]–[25].

The **Geological Models for Explorations of Dynamic Earth (GEODE)** (*PI: Pallant; Co-PIs: Lee and McDonald; DRL-1621176; \$2,698,654; 8/15/16 – 7/31/20*) project. *Summary of project results:* GEODE is in the second year of a design and development project focused on the creation of a visualization of rich real-time earthquake data and a simulation of plate tectonic dynamic processes, as well as supporting curricula and teacher professional development. Analysis of pre- and post-tests showed significant improvement (p<.001) in content and argumentation tests—students improved by effect sizes (Cohen's d) ranging from 0.62 to 0.89 SD. *Intellectual merit*: This project will contribute to the field's understanding of how engaging students with dynamic plate tectonic models supports their learning of complex Earth science concepts regarding Earth's surface features and sub-surface processes. *Broader impacts:* The GEODE project will directly involve over 5,000 students and 32 teachers from diverse school systems serving students from families with a variety of socioeconomic, cultural, and racial backgrounds. These students will be exposed to important geoscience concepts that underlie the physical processes that shape Earth's surface. *Publications:* No publications have been published to date under this award.

SIS-SIS: Collaborative Research: Building Sustainable Tools and Collaboration for Volcanic and Related Hazards (*PI: Connor; ACI 1339768; \$194,869 USF portion; 7/31/2013 – 7/30/2017*). *Summary of project results*: This project modularized hazard codes to accommodate the development of alternative approaches to modeling physical parameters. *Intellectual merit:* We have developed a method of optimizing data-fit of numerical code output using singular value decomposition with Tikhonov regularization; improving our understanding of parameter uncertainty in gravity inversion [26] and for specific eruption parameters in tephra fallout models [27]. *Broader impacts:* The project started the development of the geophysics wiki [28] and web-based model interfaces that call server-side code via PHP. *Publications:* [26], [27], [29]–[32].

NSF INCLUDES: Engaging Local Communities in Geoscience Pathways (*PI: Manduca; Co-PIs: Charlevoix, Nagle, Pandya; ICER-1649367; \$300,000; 10/1/2016 – 9/30/2018*). *Summary of project results*: This is a collaborative national pilot project that develops regionally focused Earth education pathways for students K-16+. *Intellectual merit*: The project brings together elements from several models for broadening participation in STEM and increasing success for all students. It capitalizes on findings showing that students are more engaged and invested in learning science when it is connected to local societal issues. It also makes use of authentic, real-world research experiences that increase retention and persistence. *Broader impacts*: The project demonstrates how an alliance of partner organizations with geoscience, educational, and local expertise learn from each other, mobilize resources, fill gaps, and develop new programs and pathways to greatly enhance the depth and breadth of impact. *Publications*: [33], [34].

UNAVCO Community Proposal - Geodesy Advancing Geosciences and EarthScope: The GAGE Facility (*PI: Miller; Co-PI: Charlevoix, Mattioli, Meertens; EAR-1261822; \$92,154,662; 10/1/2012 – 9/30/2018*). *Summary of project results:* The project supports the advancement of cutting-edge community geodetic research around the world. *Intellectual merit:* Geoscientists using global geodetic infrastructure coupled with leading-edge techniques are well poised to advance basic research that is in the U.S. and global public interest as the challenges of living on a dynamic planet escalate. Space geodesy furthers research on earthquake and tsunami hazards, volcanic eruptions, coastal subsidence, wetlands health, soil moisture, and groundwater distribution. *Broader impacts*: This project supports fundamental research into natural hazards spanning multiple disciplines and education and outreach activities to inform society. As global population disproportionately increases in hazards-prone coastal and tectonically active regions of the U.S. and across the globe, the societal relevance of quantifying, understanding, and potentially mitigating natural hazards grows. *Publications*: [35]; a full community bibliography and data archives are available at the UNAVCO website.

Research and Development

Theoretical Foundations

In higher education, there is already an effort to create science courses that integrate computing [36]. In addition, being able to work with programming packages (e.g., in Excel, MATLAB, Mathematica, LabVIEW) has become a commonplace expectation for scientists and engineers. The goal of these efforts is not to educate everyone to become software engineers, but to promote computational thinking (CT) to solve real-world problems unique to a variety of science disciplines. Computational thinking has been defined as concepts, skills, principles, practices, and a mindset [37]–[41]. We consider computational thinking as a practice in the same way as the National Research Council's *A Framework for K-12 Science Education* [42]. As such, integrating computational thinking into a science discipline means integrating the computational thinking practice into a subset of science practices. Figure 1 summarizes CynerG's approach, which is further elaborated below.



Figure 1. Contextualized computational practice to support science practice: A CynerG example

1. Situate computational thinking into students' authentic inquiry into real-world geohazards. *A Framework for K-12 Science Education* [42] emphasizes the importance of students experiencing

A Framework for K-12 Science Education [42] emphasizes the importance of students experiencing disciplinary core ideas through relevant science practices that reflect the ways scientists conduct their research. Such authentic science learning can be achieved by engaging students in the practices of scientists [19], [42] or by addressing contexts relevant to students' everyday lives [43], both of which can improve student motivation, science learning, and epistemological understanding [44]. However, authentic science is not necessarily accessible to students in the way it is practiced by scientists [45]. Lee and Songer [46] point out that domain-specific knowledge and science practices should be translated to the recommended level for students, e.g., as specified in the NGSS. In addition, scientists' resources and tools should be translated to accommodate student inquiry-based activities. We will develop two modules addressing volcanic activities in Yellowstone and seismic activities in the U.S. West Coast. Scientists are actively studying these regions and students are likely to be familiar with them, either directly (e.g., living near active fault lines in California) or indirectly through the news. We will engage students in the topics through this "familiarity." Importantly, it is through the use of real-world science practices—inquiry with data—modeled by manipulation of data sets to create visualizations that we will connect computational thinking with science knowledge.

2. Orient the need for computational visualizations as central to geoscientists' work.

Since Wing (2009) advocated for the inclusion of computational thinking as part of formative educational experiences in schools, many have attempted to operationalize computational thinking [37]–[40]. Despite the lack of consensus, computational thinking is generally considered as: (1) associated with identifying and solving real-world problems, (2) often related to complex systems and systems thinking, (3) involving calculations to process data and visualizations to interpret data, and (4) prioritizing efficiency and optimization usually achieved by algorithms through computational means. Since computational thinking is multi-faceted, it is impossible to implement every documented facet into learning activities. As such, we seek to identify the facets of computational thinking most prolific in the study of geohazards and to facilitate student learning of these facets. In studying geohazards, geoscientists often work with GPS data (Figure 2) and seismic data. These data are complex and requires turning it into "a landscape you can explore with your eyes," as McCandless [47] noted in his TED talk. Since the data are collected in large quantities, scientists create visualizations of the data to recognize geospatial patterns and temporal trends to test and improve their understanding of the geohazards they study. Thus, CynerG's integration of the computational practice of data visualizations focuses on engaging students in the creation, manipulation, and interpretation of large data sets in the context of learning about volcanic and seismic

hazards. Figure 1 further defines the data visualization practice consisting of modeling data through algorithms, transforming raw data into other meaningful quantities, which in turn are visualized. This process of modeling, transforming, and visualizing will repeat as students' understanding of geohazard systems improves with evidence supported by the visualizations.

3. Use a Scaffolded Visualization Programming (SVP) tool to guide creation and interpretation of spatiotemporally distributed data visualizations.

Earth science relies on observational methods to study complex real-world phenomena [48]. While the current advancement in sensor and computing technologies greatly enhances scientists' data-based investigations to study complex Earth systems, students rarely have the opportunity to engage with authentic, largescale data to learn disciplinary core ideas in Earth science. Data analysis platforms exist for students to visualize scientific data, such as Excel, the Common Online Data Analysis Platform (CODAP), [49], MyNasaData, or NOAA's Climate Explorer. CynerG is taking it one step further from these tools by allowing students to interactively simulate multiple algorithmic modeling scenarios and automate

Global Positioning System (GPS) data from UNAVCO Each GPS station has its own data file. The data is updated daily. PBO Station Position Time Series. Format Version, 1.2.0 Reference Frame, NAM08 4-character ID, LKWY Station name, LKWY_EBRY_WY1996 Begin Date, 1996-10-13 End Date, 2018-06-14 Release Date, 2018-06-16 Source file, LKWY.pbo.nam08.pos Offset from source file, -15.02 mm North, 3.32 mm East, 60.83 mm Vertical Reference position, 44.5650763353 North Latitude, -110.4002200897 East Longitude, 2424.47995 meters elevation Date, North (mm), East (mm), Vertical (mm), North Std. Deviation (mm), East Std. Deviation (mm), Vertical Std. Deviation (mm), Quality, 1996-10-13,0.00, 0.00, 0.00, 2.39, 1.85, 8.28, repro, 1996-10-14,-1.30, 0.66, 4.10, 2.26, 1.79, 7.75, repro, 1996-10-15,-0.86, -0.27, 5.46, 2.13, 1.67, 7.4, repro, 1996-10-16,1.66, -2.28, 6.44, 1.69, 1.39, 5.77, repro, 1996-10-17,0.57, 1.49, 0.28, 2.08, 1.64, 7.05, repro, 1996-10-18,1.44, 8.42, 5.34, 2.14, 1.73, 7.48, repro,

Figure 2. GPS data in raw format are difficult to interpret, but transforming them into simple visualizations allows students to see patterns and connections.

the data visualization processes for new data sets. The SVP tool embedded in curriculum modules will act as a tool for contextualized computation—where students will learn about particular aspects of

computing as they apply them to the domain under study [36]. The SVP tool will allow students to program spatially and temporally distributed visualizations through guided computer programming. By doing so, CynerG will provide a solid foundation of computing knowledge and skills, which will also provide a core computing context that will be transferable beyond this project [36]. Students will be tasked with 1) exploring how data represents volcanic or seismic hazards, 2) visualizing and analyzing data, and 3) making predictions or conducting risk assessments.

4. Use computational visualizations as evidence critical to the development of scientific arguments. Engaging students in scientific argumentation deepens their conceptual understanding, alters their views of science, and supports evidence-based decision-making [50]–[52]. Research on scientific argumentation has grown substantially over the last few decades [53]. One aspect that has been overlooked, however, is how students treat uncertainty in formulating their arguments [54]. Uncertainty can play two roles when students construct an argument. One type of uncertainty represents students' confidence in their own knowledge and ability [55]. The other type is inherent in scientific inquiry due to measurement errors, lack of conclusive theories or models, and limitations associated with current equipment and technologies. In addition, uncertainty becomes more pronounced when the study of complex systems is concerned [56] due to the fact that any representation cannot possibly contain all variables and interactions governing the system under study [57].

Geohazards are difficult to forecast and, therefore, involve a great amount of uncertainty in predicting future occurrences, as well as in estimating impact on humans. CynerG's scientific argumentation tasks involves four aspects: students will make *claims about risks* based on their *computational visualizations (evidence)* in light of their *understanding of geohazard systems (conceptual model)*, and compare the strengths and weaknesses of arguments (*uncertainty*) (Figure 1). In CynerG, uncertainty refers to the extent to which claims are constrained by evidence generated from a particular investigation context [58]. In particular, students will consider risks arising from the unpredictability of the geohazard progression. Risk refers to uncertainty that is measurable [59], when possible outcomes are related to numerically representable losses. For example, there are scientific uncertainties in predicting the exact timing of a volcanic eruption. Similarly, there are uncertainties when considering a geohazard's impact associated with people's well-being. The extent of risk depends on the degree to which it is perceived [60], as well as the vulnerability and exposure of a community. The modules will feature prompts to encourage students to consider the potential impact of a hazard and to use evidence from the real-world data to explain their assessment of short-term and long-term future risks.

Curriculum Alignment with Various Standards

The resulting technology-enhanced and computationally integrated CynerG modules will be aligned with the standards identified in *A Framework for K-12 Science Education* [42], which is the foundation for the Next Generation Science Standards [6]:

- Disciplinary core ideas related to Earth and Space Science:
 - **ESS2.B: Earth's Systems: Plate Tectonics and Large-Scale System Interactions.** "The plates move across Earth's surface...producing earthquakes and volcanoes..." (p. 182).
 - **ESS3.B: Earth and Human Activity: Natural Hazards.** "Some natural hazards are preceded by geological activities that allow for reliable predictions; others occur suddenly, with no notice, and are not yet predictable. By tracking the upward movement of magma, for example, volcanic eruptions can often be predicted with enough advance warnings to allow neighboring regions to be evacuated. Earthquakes, in contrast, occur suddenly; the specific time, day, or year cannot be predicted. However, the history of earthquakes in a region and the mapping of fault lines can help forecast the likelihood of future events" (p. 193).
- Three science practices:

- Analyzing and interpreting data: "Once collected, data must be presented in a form that can reveal any patterns and relationships and that allows results to be communicated to others. Because raw data as such have little meaning, a major practice...is to organize and interpret data through tabulating, graphing, or statistical analysis. Such analysis can bring out the meaning of data—and their relevance—so that they may be used as evidence" (p. 61). "Students need opportunities to analyze large data sets and identify correlations. Increasingly, such data sets are available on the Internet... Such data sets extend the range of students' experiences and help to illuminate this important practice of analyzing and interpreting data" (p. 62).
- **Using computational thinking:** "Computational methods are potent tools for visually representing data,... in ways that allow the exploration of patterns" (p. 65).
- **Engaging in argument from evidence:** "The production of knowledge is dependent on a process of reasoning that requires [students] ... to make a justified claim about the world...argumentation is also needed to resolve questions involving, for example, the best experimental design, the most appropriate techniques of data analysis, or the best interpretation of a given data set" (p. 71).
- One crosscutting concept:
 - **Patterns:** "The ways in which data are represented can facilitate pattern recognition and lead to the development of a mathematical representation, which can then be used as a tool in seeking an underlying explanation for what causes the pattern to occur" (p. 86).

Curriculum Modules

The project will develop two curriculum modules that feature computationally integrated, inquiry-based activities in which middle and high school students will explore case studies of geohazards. In each two-week curriculum module, students will develop three types of visualizations, including 1) spatial representations of key data; 2) dynamic representations of change over time; and 3) projected risk maps. The modules will feature specific prompts to encourage students to consider the impact of the geohazards, to use evidence from the visualizations, and to communicate potential impact on communities in the event of a hazard. Through uncertainty-infused argumentation [10] students will make claims about geohazard risks based on their visualizations and describe how uncertainty plays a role in the evaluation of the risks. Students will be introduced to the hazard as well as to programming necessary to develop the visualizations. As the modules progress, students will incorporate geoscience and computational knowledge to explore more complex visualization problems.

The case studies will rely on the scientific process that the USF Co-PIs engage in while conducting their own research. As volcano scientists, their research begins by observing a phenomenon, collecting data, developing visualizations and models of a system, and then applying their understanding to explore predictability and impact of the volcano they are studying. For example, the USF scientists' research looks at how volcanic earthquakes could be used for monitoring future volcanic behavior at the Telica Volcano in Nicaragua [62]. As part of their research, the scientists analyze GPS and seismic data and create visualizations to answer questions about how, for example, earthquake frequency changes over time prior to an eruption. Middle and high school students will necessarily need to grapple with problems that are smaller in scope than practicing scientists. Nonetheless, the access to these scientists, their research methodology, and their visualization programming code will help the project consider how to scaffold concept development and programming of the visualizations.

UNAVCO will provide students access to an unprecedented wealth of geophysics data to investigate earthquake and volcanic geohazards. UNAVCO manages the geodetic component (the Plate Boundary Observatory (PBO)) of the National Science Foundation-funded EarthScope project, a 15-year study of the structure and evolution of the North American continent and the processes that cause earthquakes and volcanic eruptions. The EarthScope project includes thousands of high-precision GPS, seismic, and other geophysical instruments. The PBO is a network of over 1,100 continuously operating GPS stations extending from Alaska to southern California and eastward across the continental U.S. By their nature these data are complex and significant expertise is required to process, interpret, and use them. Of critical importance is that UNAVCO produces a processed GPS data set open to the science community and the public, and has developed more user- and spreadsheet-friendly file formats (.csv) and data products that can be incorporated into curricular materials. UNAVCO will ensure that data sets used in this project will be accessible by middle and high school students. The value of these data is the ability to detect and monitor millimeter-scale surface motions at discrete locations. Through the integration of GPS data into CynerG's two proposed modules, students will use the same data that geophysicists and geodesists use in their scientific research.

Module 1: Yellowstone is a supervolcano. What are the risks if Yellowstone's supervolcano erupts?

Yellowstone National Park sits over a giant active volcano and is capable of eruptions thousands of times more violent than the 1980 Mount St. Helens eruption. Geoscientists would like to know if and when

Yellowstone will erupt and, if it does erupt, what are the potential consequences. In order to study the volcano, geoscientists need to conceptualize processes occurring under the ground as well as subtle deformational changes at the surface. Currently, scientists are collecting high-precision geodetic (GPS) and seismic data to better understand changes happening within the volcano. This data helps scientists monitor changes and assess potential risks if it were to erupt. Like scientists, students will explore the volcanic processes, develop visualizations of both ground motions based on GPS data and earthquakes around the caldera, create dynamic representations of how the caldera is changing over time, and develop projected risk maps in order to identify places that might be adversely affected in the event of a hazard (Figure 3).



Figure 3. The United States Geological Survey risk map based on projected distribution of ash from a Yellowstone supereruption. Students will create maps similar to this.

Module 2: California is overdue for a big earthquake. What are the risks?

The well-known San Andreas Fault is one of seven significant fault zones in the San Francisco area. Though people who live in the area experience earthquakes all the time, the USGS estimates that there is a 63% probability of an earthquake 6.7 or higher occurring by 2037. In this module, students will explore seismicity and ground motions in and near California. Focusing on surface motions, earthquake frequency, and magnitude, students will create dynamic visualizations showing rates of plate motion in the region and will develop a risk for a large earthquake (magnitude greater than 6.7) centered in Northern California.

An integrated learning task example

Santiago is working with Audrey in his Earth science class to try to understand what is happening in the caldera and geyser basins in Yellowstone National Park. Santiago is particularly interested because he visited Yellowstone over his summer break. Audrey has become excited after reading that scientists think the supervolcano will erupt again. Santiago and Audrey are investigating how the caldera is changing. Following prompts in the curriculum, they learn that high-precision GPS stations have been installed throughout the Yellowstone region with detailed and timely measurements of the changing surface. Audrey is impressed that the GPS stations can measure changes of only a few millimeters. Santiago and Audrey learned on the previous day how to create a graph that shows the location of one GPS station. Santiago now asks, "How do we plot more than one GPS station?"

At this point, their teacher, Ms. Brau, displays the data set for the class and asks students to discuss how the data might help them solve the problem of showing change along the surface of the caldera. One student suggests that they need to know the location of the GPS stations relative to each other while another mentions they have to show how the surface has changed. As they begin to agree on a plan of action, Ms. Brau shows the students an example of the code they created on the previous day. "Yesterday you learned how to plot one point. Now let's consider how to place several GPS stations into a visualization. How might we add to the code shown here?"

Santiago and Audrey are excited to modify their code as part of this challenge. They had already figured out how to place two GPS stations in their graph, though they didn't want to repeat the code for all 18 GPS locations. Ms. Brau, who has been circulating around the class, asks them how they might more efficiently place all GPS stations on the graph. The three of them brainstorm together and make changes to the code. They can see the graph changing as they work (Figure 4). Ms. Brau sees the results and reminds them to label the y-axis. Then, Audrey exclaims "It would be so cool if we could show each station moving! We could see what is happening over time." Ms. Brau smiles. That's what they'll do tomorrow.

Technology Development

A Scaffolded Visualization Programming (SVP) tool

The project will create an online SVP tool that will evolve as students acquire new programming concepts, exposing the student to new ideas and tool affordances. This resource will leverage a block programming paradigm at first, gradually moving the learner towards more sophisticated text-based programming in JavaScript.

A common frustration for new programmers is the precise syntax and typographic requirements of writing code. Block programming languages remove these common hurdles when learning languages such as C or Python. A programming language like Google's Blockly allows learners to concentrate on the underlying programming concepts. Block programming provides visual cues that guide learners towards creating useful programs. Our SVP tool will connect CC's JavaScript simulation framework to a custom build of Google's Blockly visual programming library. Our extensions to Blockly will allow students to import authentic research data and explore the data using JavaScript visualization toolkits. Students will be able to take advantage of software libraries to facilitate creating graphs, working with large data sets, and creating risk maps. These tools simplify programming tasks that are unrelated to and possibly distracting from the geoscience visualization goals.

Initially, a student will see only a limited set of block types to solve content-related challenges. Additional blocks will be made available over time. Using Blockly's "switchable" view students will have access to the underlying code. This affordance converts the visual block program into human readable and machine executable JavaScript. With our SVP tool, students will be able to make changes to the JavaScript within their block program, or develop new blocks and see immediate changes in the generated code (Figure 4). We will pair the discoverability of block programming with responsive plots, maps, and visualizations that update instantly when the student's program changes. We anticipate that this combination will provide a productive low-friction live-coding environment where students see the results of their experiments and iterate quickly on new solutions.

As the programming language that powers the Internet, JavaScript is available in every web browser, making it the most ubiquitous and open programming language of our time. It also has a low barrier to entry because it allows variables to seamlessly change type, for example, from a string variable to a number to an object variable. Further, there are no build or compilation codes required, making it easy to try things out in the browser. But despite its accessibility, JavaScript uses a syntax similar to many other programming languages, so students of JavaScript will find that they can transfer their knowledge to reading and writing programs in C and Java, too. Our SVP tool will be delivered within LARA (Lightweight Activities Runtime and Authoring Environment), Concord Consortium's web-based open-source courseware platform in which students work through scaffolded experiences that guide the exploration. LARA includes online embedded assessment prompts that collect student responses in real time and log students' real-time actions.

Menu 🗮	Activity 2: How much movement?	23456789
Working	g with lists	Welcome, Anonymous
Below is the co	- code you developed yesterday to draw a circle on the graph from one piece of collect	ed GPS data.
"Caldera-Set" i altitude for eac	t" is a dataset of 18 different GPS stations. Modify the code you wrote yesterday to dia ach GPS unit in the data sample station in a visualization.	splay the relative change in
Experiment	nt #3	
Blocks for each item gps do set r to Piot to graph x coordinate y coordinate	<pre>ps_datum in list create list from data</pre>	DataFile("Caldera set"); praph");
< Back		Next >

Figure 4. The SVP tool embedded in the LARA courseware system. Students can change block code (left) or text code (top right) and immediately see changes in the visualization (bottom right).

Research Questions

RQ1. (*Improving understanding through computational data visualization*) How do students translate their understanding of a geohazard into an algorithmic model to create visualizations from GPS data? How do students interpret data represented in visualizations to improve their understanding? What types of teacher, curricular, and programming supports are necessary to engage students in creating and interpreting visualizations?

RQ2. (*Improving uncertainty-infused scientific argumentation supported by computational data visualization*) How do students use visualizations they create in formulating scientific arguments to assess risks related to a geohazard? How do students conceptualize and manifest scientific uncertainty involved in their risk assessment? How do students quantify and explain risks and compare different sources of risks?

RQ3. (*Curricular impact on student learning*) Does CynerG's curricular approach improve students' understanding of geohazards and data-based scientific argumentation associated with risk assessment? To what extent, for whom, and under what conditions is this approach useful?

Research Plan

Research will occur in two phases. The first phase involves design-based research to iteratively refine the modules, the SVP tool, and the assessments. We will also investigate the curricular, programming, and teacher supports necessary to allow students to create and interpret computational visualizations through the SVP tool. Using a delayed cohort pre-post test design, the second phase will investigate the impact of integrating the computational practice of data visualization on student learning.

Phase 1: Design Studies (Year 1 and Year 2)

We will conduct a series of design studies: first with the SVP tool, followed by two curriculum modules. Established learning theories, available research results, and our prior research and development experiences will inform initial design decisions. Through iterative design-test-analyze-redesign processes we will refine the SVP and curriculum modules as well as underlying theories used to develop them [63]. Each module will undergo three design cycles over a two-year period. The design studies phase will focus on answering research questions 1 and 2.

Design Cycle 1: SVP tool prototyping and testing with scientists, lead teachers, and student groups. A prototype SVP will be developed and tested with scientists and four high school teachers. We will make revisions based on their reviews. The revised SVP will then be tested using "clinical" trials with students working in small groups (n=8). Students will be drawn from high schools local to CC's Massachusetts and California offices and will carry out several inquiry tasks. We will use semi-structured think-alouds to prompt student responses. The goal is to focus on user experience and interaction with the tool, assessing the task difficulty originating from the coupling of inquiry-based tasks with computational visualizations, and clarifying and identifying programming support features critical for students to create visualizations.

Design Cycle 2: Curriculum prototyping and testing with four lead teachers. Informed by the research literature, relevant science education standards, and computational thinking recommendations, project staff will develop performance expectations for the modules related to content understanding and uncertainty-infused argumentation addressing geohazard risks and computational data visualizations as evidence. We will *prototype* early-stage activities with four lead teachers in the first year (Table 1). Two teachers will implement the prototype volcano activities and the other two will implement the prototype earthquake activities. Note that a teacher will be recommended by the California school district, along with the three named teachers in the table. Teachers will also implement pre- and post-tests and student demographic surveys. A total of 200 students will participate, assuming 50 students per teacher.

Design Cycle 3: Full curriculum testing by four lead teachers. Based on what we learn from Design Cycle 2, we will create full versions of the two modules. The modules will be tested with the same four teachers (n=4) and their new cohort of students (n=200) in Year 2. The teachers will take part in a three-day professional development workshop during the summer prior to their module implementation and will also receive one-on-one support from project staff before and during their implementations.

Phase 2: Curriculum Implementation Study Using Delayed Cohorts (Years 2 and 3)

Research in Phase 2 will focus on answering research question 3 that investigates the added benefits of integrating the computational practice of data visualizations with the teaching about geohazards typically taught without the proposed computational practice in this project. For this study, we compare student learning outcomes using delayed cohorts where the same teachers teach the traditional content to the first cohort of students one year and the CynerG modules to the second cohort of students the following year. To do this we will collect information from teachers about the materials and implementation used for the first cohort. To implement this delayed cohort design, we will recruit 8 teachers from the Mountain Diablo Unified School District in California and a pool of teachers with whom we have worked in past NSF-funded projects. We will select teachers that represent diverse school settings in terms of students' language status, gender, computer experience, grade level, and school locale (suburban, urban, rural). Eight new teachers will provide baseline pre/post-test data in Year 2 using their own teaching materials. In Year 3, they will implement both revised CynerG modules as a replacement for their own materials. Apart from teachers in the delayed cohort research, the original four lead teachers from Years 1 and 2 will continue to implement the final version of the CynerG modules. Altogether, 12 teachers and 600 students (= 12 teachers x 50 students) will participate. All teachers will take part in a three-day face-to-face workshop during the summer prior to Year 3 implementation.

School	Teacher	State	School Setting	Minority	Free/Reduced lunch
Mountain Diablo	Recommended by	CA	urban/suburban	45%	75%
unified school district	district coordinator				
Olive Grove Charter	Rebecca Reid	CA	rural	40%	20%
School					
Framingham High	Emily Rathmell	MA	urban	36%	20%
Rock Castle High	Stephanie Harmon	KY	rural	1%	50%

Table 1. Lead teacher participants

Data Collection and Analysis

Every time a module is implemented, the following data will be collected and analyzed:

Pre/post-test data collection and analysis. Students will take online pre- and post-tests that assess their content understanding of geohazards and evaluate their uncertainty-infused argumentations using evidence from computational data visualizations aimed at assessing risks to humans. We will also collect demographic information such as gender, language, computer experience, and grade level through an online survey. Student learning outcome variables will be created for content understanding and scientific argumentation. On each learning outcome variable, we will pull all student data together and apply repeated measures ANCOVA with the teacher as a fixed effect and other student demographic variables as covariates. During Design Cycles 2 and 3, this repeated measures ANCOVA analysis will allow us to examine how variations in teacher and student implementation impact student learning, as well as for whom the CynerG modules are beneficial. For the delayed cohort study, we will add two additional variables into the ANCOVA analysis related to the treatment (1 for students who CynerG modules and 0 for prior year's students who do not) as a fixed effect and teacher as a random effect. This analysis will test whether the treatment results in a significant change in student gains on the outcome variables from the pre-test to the post-test while controlling for teacher-level variations.

Module data collection and analysis. Each module will include embedded prompts that elicit students' responses, including 1) selecting an answer from multiple choices, 2) writing descriptions or explanations, 3) computational visualizations students develop, 4) drawing predictions, and 5) developing uncertainty-infused scientific arguments. Each argumentation task will include structured prompts related to risk claim, explanation of the claim based on evidence and conceptual model, uncertainty rating, and uncertainty attribution based on the strengths and weaknesses of evidence [10].

Students' responses to embedded assessments in the modules will all be recorded automatically by the server and will be retrieved later and analyzed to examine sense-making with data visualizations, use of evidence in scientific argumentation, and development of scientific arguments to assess risks.

Log data analysis. Time-stamped log data track student interactions with the modules and the SVP tool, including codes written and executed by students and how they modified the codes, what visualizations students created, how much time students spend on the construction, running, and revision processes, and how students enhanced the data visualizations to improve clarity. Additionally, log data will track when and what students type in response to each prompt and when and how students go back and forth between the data visualizations and argumentation tasks to improve coordination between their understanding and data analysis. Log data analysis, therefore, will be used to understand students' computational data visualization practices as they relate to other activities featured in the curriculum modules such as learning content and formulating arguments.

Assessment Instrument Development and Validation (Year 1 to Year 2)

Assessment instrument 1: Understanding of the science of geohazards will be measured using the knowledge integration framework [64] and knowledge integration scoring (KI) rubrics [65], which can measure the depth of student understanding related to how and why scientific phenomena occur. The KI scoring rubrics are designed to measure students' abilities to elicit and make links between ideas relevant to a scientific context [66]. Items that have used the KI framework have been validated in classroombased trials for psychometric rigor [65], sensitivity to instruction that fosters integrated understanding of science across physical, biological, and Earth sciences [66], [67], and learning progression in energy [68]. KI-based assessments project students' performances on a unidimensional construct according to Rasch-Partial Credit Model analysis with a Cronbach Alpha value of .81 for Earth science items [66]. Assessment instrument 2: Uncertainty-infused scientific argumentation with computational data visualizations will be assessed using a set of items that measure the extent to which students make reasonable and reliable claims about geohazard risks based on computational data visualizations, as well as their understanding of geohazard systems. In particular, we will be interested in eliciting the extent to which students recognize limitations associated with their risk claims and evidence-based justification and how uncertainty plays a role in their assessment of risk. The uncertainty-infused scientific argumentation construct was developed and validated using Rasch Analysis based on Partial Credit Model [10]. Rasch analysis results indicate that students' claims, explanations, and uncertainty explanations formulate a unidimensional construct and had an acceptable model fit with a reliability of 0.91 Cronbach Alpha. In CynerG, we will use this uncertainty-infused scientific argumentation framework to draft six sets of tasks where various geohazard risks will be evaluated.

Assessment instrument validation. We will design knowledge integration items and uncertainty-infused argumentation items related to geohazards. For each module, the first version of these items will be administered as a post-test in Design Cycle 2 and students' responses will be analyzed qualitatively to identify whether items elicit expected responses from students. We will modify the items according to the analysis results. In Design Cycle 3 during Year 2, we will administer the revised items as pre/post-tests. We will analyze students' responses to the post-test (200 students from four teachers participating in Design Cycle 3 and 400 students from eight teachers who provide baseline data without learning CynerG modules) to establish the construct validity. The construct modeling approach [69] consists of four steps: (1) a construct map is theorized from the relevant literature on the target construct; (2) items that elicit various levels on the construct map are selected for an instrument; (3) student responses are collected on the instrument; and (4) appropriate item response models are applied to student response data. We will use Rasch Modeling of student responses [70], [71] to establish the validity of each instrument [72]. To ensure Rasch Modeling is appropriate, we will test for multi-dimensionality with exploratory factor

analysis (EFA) using principal axis factoring with a promax rotation [73]. We will also test for local dependence [74]. Moreover, since the instrument is administered as pre/post-tests, we will examine the items' sensitivity to CynerG modules by analyzing both pre-test and post-test. These instruments will be used again, with some minor modifications if needed, for Year 3.

Teacher Professional Development

Teacher professional development is critical to ensure faithful implementation of CynerG modules. The project will offer a three-day in-person workshop to four teachers in the summer of Year 1, and 12 teachers in the summer of Year 2. The workshop will be an integrated mix of pedagogical and content learning in both Earth and space science and in helping teachers build knowledge, skills, and confidence in teaching computational visualizations through the SVP tool. In addition, sections of the workshop will be devoted to supporting teachers in developing enactment plans based on their local contexts. A collection of video tutorials will be developed based on the in-person workshop materials and provided on the project website for teachers to turn to when they prepare for implementation.

Partners and Responsibilities

Amy Pallant will serve as Principal Investigator. She will direct the development of the modules and curricular materials and be responsible for the overall coordination and budgeting of the project.

Hee-Sun Lee, Ph.D., **(**Co-PI) will lead the research on assessment development and student learning of uncertainty-infused scientific argumentation and content understanding. She will develop the research plan and guide the data collection and analysis, and will coordinate publication efforts with partners.

Noah Paessel (Co-PI) will lead the development of the SVP tool and work with curriculum developers on designing programming tasks.

Jie Chao, Ph.D., **will** conduct research based on her extensive research experience in computer science education, STEM education, and technology-enhanced learning environments.

Charles Connor, Ph.D., (Co-PI) will oversee the USF portion of the budget, provide scientific expertise, and share code developed for visualizations.

Mel Rodgers, Ph.D., a volcanologist at USF, will bring her experience as a scientist, code developer, and outreach and engagement activities planner to help the team design and develop materials.

Sylvain Charbonnier, Ph.D., a volcanologist at USF, will bring his expertise in geohazard research, data visualization, and hazard communication to help the team design and develop materials.

Donna Charlevoix will supervise project activities at UNAVCO, ensure that the necessary UNAVCO resources and support are available, and assist with the education research.

Shelley Olds from the UNAVCO ECE Program will work closely with the CC team to develop materials, incorporating scientific data from UNAVCO, and will co-lead the teacher workshops.

Mechanisms to Assess Success of the Project

Advisory Board

An external board will provide project evaluation, including objective external review of the curriculum, assessments, and the SVP tool, as well as feedback on design changes and research findings. They will prepare reports for project staff and the NSF. They will meet face-to-face in the first two years, and will meet with the staff via remote video throughout the project and for an online meeting in the third year. **Dr. Kristen Gunkle** is an associate professor of science education at the University of Arizona. Her work

focuses on environmental science literacy and teacher preparation.

Dr. Ben Fry is founder and principal of Fathom Information Design, a studio in Boston focused on understanding complicated data problems.

Stephanie Harmon is a high school Earth Science teacher at Rockcastle County High School in Kentucky. She will provide practical insight into classroom challenges and field test the modules.

Dr. Dorothy Wallace is a professor of Mathematics at Dartmouth College with special interest in problem-solving and quantitative reasoning.

Dr. Keith Maull is a software engineer at the University Corporation for Atmospheric Research (UCAR) and focuses on data science, in particular, the analysis and visualization of big data.

Dissemination

The project will create two online learning modules, teacher guides, assessments, the SVP tool, and research. All materials will be available in electronic forms on the CC and UNAVCO websites. The SVP tool and curriculum materials will be licensed under open-source code and open content licenses and will be freely distributed to teachers, curriculum designers, and researchers. The partners will promote the materials through various digital channels, including blogs and social media. Additionally, all partners will promote project materials and research findings through presentations and workshops at conferences (e.g., National Science Teachers Association, National Association of Research in Science Teaching, and International Society of the Learning Sciences) and through articles published in peerreviewed journals in science education (*Journal of Research in Science Teaching, International Journal of Science Education, Science Education,* and *Journal of Geoscience Education*), learning sciences (*Journal of the Learning Sciences*), and teachers (*The Science Teacher*). The @Concord biannual newsletter, distributed for free to over 30,000 digital and print subscribers, will be another communication venue.

Broader Impacts

The project will benefit society by equipping young people with computational and problem-solving skills applicable to future learning endeavors and greater knowledge of how the process of science research can inform society about hazards and their potential impacts. Integrating computing into Earth science classrooms means computational thinking will reach a different audience than traditional computer science classes. Project materials will be developed with close attention to the needs of diverse students and will be implemented in a wide range of schools, including those that serve underrepresented students. This addresses the issue of girls and other underrepresented groups self-selecting into and out of computing classes [75]. Students will have foundational programming experience in JavaScript coding, which can help them to learn the coding syntax for other programming languages, preparing them for potential future study and careers. The project will collaborate with 12 Earth science teachers across the country and reach 800 students who will directly benefit from project resources. In addition, educators taking the initiative to bring computing experiences into their science classrooms will have access to all the project resources through the partners' websites.

Intellectual Merit

CynerG will create novel learning opportunities that can lead to enriching science learning through realworld science contexts while also enhancing learning about computation through computer applications. This project builds on extensive prior and current work by the proposers, as well as contemporary research and development in STEM education. The team includes experts in geohazards, geodesy, Earth science education, research, and technology. The project will research the synergy between interest in geohazards, access to a wealth of geophysics data, and the development of computational thinking competencies. The project builds on theoretical foundations in authentic science, data science, riskinfused argumentation and computational thinking. The development and research will advance the fields of interdisciplinary learning and provide strategies for supporting teachers and students when implementing this type of project in classroom settings. This project will contribute to the field's understanding of how to support students' creation of computational visualizations and analysis of realworld data in order to improve their conceptual understanding of geohazards.

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